

## TURBOCHARGER WITH HYDRODYNAMIC FOIL BEARINGS

## BACKGROUND OF THE INVENTION

The invention relates to turbochargers used for boosting the performance of engines such as diesel and gasoline automotive engines and the like.

5 Turbochargers for diesel and gasoline automotive engines have conventionally employed oil-lubricated bearings. The turbocharger is connected to the engine oil system and engine oil is supplied into the bearing housing of the turbocharger to lubricate the bearings, and the oil is then discharged from the bearing housing and returned to the engine oil system.

10 Oil-lubricated turbochargers are prone to oil seal failures. If the oil seal on the turbine side of the turbocharger fails and allows oil to leak into the turbine, the oil ends up being discharged into the engine exhaust system, which can increase undesirable emissions from the engine.

The durability of an oil-lubricated turbocharger is highly dependent on the engine lubrication system. The now common use of low-viscosity oils and high engine oil temperatures to reduce friction adversely affects the stability and durability of the turbocharger bearing system, as well as the effectiveness of the oil seals. On the other hand, operation under very cold conditions can lead to a delay of the oil pressure reaching the turbocharger and can also result in turbo bearing durability problems.

20 Additionally, oil-lubricated turbochargers are restricted to being used in a particular horizontal orientation, since they depend on gravity for draining the oil from the bearings. As a result, the engine or vehicle designer does not have much freedom with respect to placement of the turbocharger.

25 Certification under 37 C.F.R. §1.10  
This correspondence is being filed by Express mail addressed to  
Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450  
on Date: 2/28/04  
Express Mail No.: EA 783376905 w  
30 By: [Signature]  
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These and other drawbacks of oil-lubricated turbochargers have led industry to seek to develop a practical turbocharger employing hydrodynamic air foil bearings. Foil bearings have been used in air cycle machines (turbomachines used in a cooling cycle where air is the working fluid) for the aerospace industry since approximately 1970. Such air cycle machines are used, for example, for supplying cooling air for electronics in military aircraft, and for supplying air for cabin climate control systems in commercial aircraft. It is relatively easy to adequately cool foil bearings in an air cycle machine because the machine operates at a relatively low temperature, typically a few hundred degrees Fahrenheit. However, prior to the present invention, it is believed no production turbochargers incorporating foil bearings have been developed, at least in part because difficulties have been encountered in adequately cooling the foil bearings. Without adequate cooling, foil bearings tend to have short useful lives.

Thus, while the benefits of incorporating foil air bearings into a turbocharger are well understood, significant technical challenges have to be overcome to develop a practical design. These challenges include developing an adequate bearing housing thermal design and cooling system to avoid overheating the foil coatings, providing adequate seals to prevent bearing contamination by engine oil and combustion products, and developing a high stiffness shaft design to avoid shaft instability at high speeds.

The present invention addresses the above needs and achieves other advantages.

#### BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

FIG. 1 is a schematic depiction of a turbocharged engine system in accordance with one embodiment of the invention;

FIG. 2 is an axial cross-sectional view of a turbocharger in accordance with an embodiment of the invention;

FIG. 3 is an axial cross-sectional view, on an enlarged scale relative to FIG. 2, showing the center housing and bearings of the turbocharger in greater detail;

FIG. 4 is an axial cross-sectional view of the center housing;

FIG. 5 is a cross-sectional view on line 5-5 in FIG. 4;

5        FIG. 6 is an exploded perspective view of a bearing assembly of the turbocharger in accordance with one embodiment of the invention;

FIG. 7 is an axial cross-sectional view showing a thrust bearing assembly in accordance with an embodiment of the invention;

10       FIG. 8 is a cross-sectional view on line 8-8 in FIG. 7, showing details of one of the journal bearings in accordance with one embodiment of the invention;

FIG. 9 is an exploded perspective view of a thrust bearing assembly in accordance with an embodiment of the invention.

#### DETAILED DESCRIPTION OF THE INVENTION

15       The present inventions now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the invention are shown. Indeed, these inventions may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

20       FIG. 1 schematically depicts an engine system **20** in accordance with an embodiment of the present invention, employing an "oil-less" turbocharger having foil bearings. The system **20** includes an engine **22**, shown as a reciprocating internal-combustion engine. The engine can be of various types, including diesel engines or gasoline engines, having various numbers and arrangements of cylinders. The engine  
25       includes an air intake **24** through which air is supplied to the engine for mixing with fuel to be burned in the cylinders of the engine, and an exhaust **26** through which combustion gases produced in the cylinders are exhausted.

The system **20** includes a turbocharger **50** comprising a compressor **60** and a turbine **70**. The turbocharger boosts engine power by compressing the air that is supplied to the air intake **24** of the engine. Thus, air is drawn into the compressor **60** through a suitable inlet duct **28**; the air can be filtered by an air filter **30**. The compressor **60** compresses the air and supplies it, via an intake duct system **32**, to the engine air intake **24**. As known in the art, an intercooler or heat exchanger **34** can be provided in the air intake system for cooling the compressed air before it is fed into the engine. As further described below, foil air bearings of the turbocharger **50** are cooled by cooling air drawn from the intake system downstream of the compressor **60**. Preferably, the cooling air is drawn from a point downstream of the intercooler **34**, via a cooling air line **36**. An air filter **38** can be provided in the cooling air line **34** for filtering out oil vapor that may be contained in the air. Oil vapor in the cooling air also can be reduced or minimized by using a reverse pitot **40** (i.e., a pitot tube that faces away from the oncoming air stream) for extracting the cooling air from the intake duct **32**. When the air filter **38** is included, the reverse pitot **40** may not be necessary and can be replaced by a forward pitot or by a flush static tap. On the other hand, when the air filter is omitted, it may be preferable to employ the reverse pitot **40**.

FIG. 2 shows a turbocharger **50** in accordance with one embodiment of the invention, which can be used in an engine system such as shown in FIG. 1. The major components or modules of the turbocharger include the compressor **60**, the turbine **70**, and a center housing and bearing assembly **80**. The compressor **60** comprises a compressor housing **61** that defines an axially extending air inlet **62** through which air to be compressed is received into the compressor assembly. Mounted within the compressor housing is a compressor wheel **63** that is rotatable about a central longitudinal axis of the turbocharger. The compressor wheel **63** is mounted on one end of a rotatable shaft **52** that extends longitudinally through the center housing and bearing assembly **80** and connects to the turbine wheel as described below. The shaft **52** comprises a two-part assembly having stepped shaft part and a shaft sleeve. The stepped shaft part defines a larger-diameter portion **52a** adjacent to and joined with the turbine wheel and a smaller-diameter portion **52b** joined to the larger-diameter portion and extending through a central bore in the compressor wheel **63**; an end of the smaller-diameter portion is threaded and a nut **53** is threaded onto the end to

secure the compressor wheel. The shaft sleeve **52c** is press-fit about the smaller-diameter portion **52b** and has an outer diameter equal to that of the larger-diameter portion **52a**.

The compressor wheel supports a plurality of compressor blades **64**. The housing **61** and the wheel **63** define a flow path therebetween, and the blades **64** occupy the flow path. The flow path is oriented generally axially at an upstream side of the compressor wheel, and then turns radially outwardly so that it extends generally radially outwardly at a downstream side of the wheel adjacent the trailing edges of the blades **64**. Air is ingested through the inlet **62** into the row of blades **64** and is compressed as it travels along the flow path through the compressor; the compressed air is discharged radially outwardly into a generally annular volute **65** defined by the compressor housing. From the volute **65**, the compressed air is supplied via a discharge pipe (not shown) to the engine air intake duct **32** (FIG. 1). The compressor illustrated in FIG. 1 is generally referred to as a radial compressor, or a centrifugal compressor; however, the invention is not limited to any particular type of compressor, and other types may be used, such as axial-flow compressors.

The turbine **70** includes a turbine housing **71** that defines a central cylindrical bore **72** therethrough. The turbine housing also defines a generally annular volute or chamber **73** that surrounds the central bore **72** and opens into the bore at a radially inner side of the chamber. Mounted on the opposite end of the shaft **52** from the compressor wheel **63** is a turbine wheel **74** that supports a plurality of turbine blades **75**. In a typical installation of the turbocharger, hot exhaust gas from the engine is supplied via a suitable exhaust duct system **26** (FIG. 1) into the chamber **73**. The exhaust gas flows generally radially inwardly (although it can also have an axial component) from the chamber into the row of turbine blades **75**, which are appropriately shaped so that the turbine wheel **74** is rotatably driven by the exhaust gas. The exhaust gas is expanded to a lower pressure as it passes through the turbine, and is then discharged from the turbine housing **71**. Mechanical power generated by the turbine is used to drive the compressor via the shaft.

With reference particularly to FIGS. 2-5, the center housing and bearing assembly **80** includes a center housing **90** having a central bore therethrough, coaxially arranged with respect to the rotational axis of the compressor wheel. A foil

air bearing assembly **100** is mounted within the bore of the center housing. The foil air bearing assembly **100** defines a central bore therethrough, and the shaft **52** extends through the bore in the bearing. During operation, there is a radial clearance between the shaft and the bearing bore so that the shaft can rotate with respect to the bearing;  
5 air is supplied into the bearing assembly via a supply passage **94** defined in the center housing. The air that has lubricated and cooled the bearing assembly is discharged from the center housing via a discharge passage **96**. It should be noted that at rest and at low speeds, the foil is preloaded against the shaft and there is no clearance. Once the shaft is rotating fast enough to generate sufficient pressure, the foil is pushed away  
10 from the shaft and the clearance results.

With reference primarily to FIGS. 3 and 6-9, the foil air bearing assembly **100** includes a first foil journal bearing **120**, a second foil journal bearing **140**, and a foil thrust bearing assembly **160**. In the illustrated embodiment, the thrust bearing assembly **160** is disposed between the journal bearings **120**, **140**. This is referred to  
15 herein as a “center-mounted thrust bearing” configuration. Each of the journal bearings is retained in an annular bearing carrier removably installed in the bore **92** of the center housing, and has one or more foils disposed along the inner surface of the bearing carrier surrounding the shaft **52**. In the description that follows, the term “outboard” is used to refer to the compressor side of the turbocharger and the term  
20 “inboard” is used to refer to the turbine side of the turbocharger. Thus, the first journal bearing **120** may also be referred to as the outboard journal bearing, and the second journal bearing **140** may be referred to as the inboard journal bearing.

The first or outboard journal bearing **120** comprises a first annular bearing carrier **122** that is installed in an outboard portion of the center housing bore **92**  
25 adjacent the compressor. The bearing carrier **122** can be made of various materials; heat transfer to the journal bearing can be reduced by making the carrier of a poor thermally conducting material such as stainless steel, ceramic, or the like. The bearing carrier **122** has an outer surface that is generally cylindrical and is made up of an annular maximum-diameter portion **123**, an annular recess **124**, an annular surface  
30 **125** at the outboard end of the bearing carrier, and an annular surface **130** at the inboard end of the bearing carrier. The recess **124** in the outer surface is located between the maximum-diameter portion **123** and the annular surface **125**. The

maximum-diameter portion **123** has a diameter less than that of the outboard portion of the center housing bore **92** in which the bearing carrier **122** is installed. To locate the bearing carrier **122** radially within the bore **92**, an undulating ring **131** is mounted about the bearing carrier within the recess **124** in its outer surface. The ring **131**  
5 undulates in the circumferential direction; its undulations project radially out from the outer surface of the bearing carrier and abut the inner surface of the bore **92** in the center housing. The ring **131** advantageously can comprise a tolerance ring. The ring is formed of a metal. To minimize heat transfer from the center housing to the bearing carrier **122**, the ring **131** advantageously comprises a material having a  
10 relatively low thermal conductivity, such as stainless steel or the like. In addition to its heat transfer-reducing function, the ring **131** may also help attenuate vibration and/or noise from shaft unbalance.

The outboard end face **126** of the bearing carrier **122** has three radially extending recesses **127** formed therein and circumferentially spaced about the axis of  
15 the carrier. The end face **126** abuts a support ring **132** removably installed in the outboard end of the center housing bore **92**. The support ring **132** is prevented from moving axially in the outboard direction (i.e., toward the compressor) by a beveled retaining ring **133** that is adjacent the outboard face of the support ring **132** and fits into an annular groove **134** in the inner surface of the center housing bore **92**.

20 The inner surface **128** of the outboard bearing carrier **122** is cylindrical and includes three circumferentially spaced slots **129** (which are circumferentially staggered with respect to the recesses **127** in the outboard face of the carrier). The slots **129** (only two of which are visible in FIG. 6) extend axially along the full length of the inner surface **128**. As further described below, one of the slots **129** provides an  
25 anti-rotation feature for a foil assembly installed along the inner surface **128** of the bearing carrier; the other two slots **129** allow cooling air to pass therethrough behind the foil assembly.

As noted, a foil assembly is mounted within the bearing carrier **122**. With particular reference to FIG. 8, the foil assembly includes a pair of generally tubular  
30 outer and inner spring elements **135** and **136**; the inner spring element **136** is disposed coaxially within the outer spring element **135**. Each of the spring elements undulates in the circumferential direction so as to define undulations that extend axially. The

radially outer surfaces of the undulations of the outer spring element **135** abut the inner surface **128** of the bearing carrier **122**. The radially outer surfaces of the undulations of the inner spring element **136** abut the inner surface of the outer spring element **135**. Each of the spring elements is split along an axial split line and the  
5 resulting edges of each spring element are bent to extend radially outwardly and are inserted into one of the slots **129** in the inner surface of the bearing carrier. The foil assembly also includes a generally tubular foil **137** coaxially disposed within the inner spring element **136** adjacent the outer surface of the shaft sleeve **52c**. At zero and low speeds, the foil **137** is against the shaft sleeve **52c**; when the rotational speed becomes  
10 great enough to develop sufficient pressure, the foil is pushed away from the shaft sleeve so that a clearance exists between them. As with the spring elements, the foil **137** is split along an axial split line and the resulting edges are bend to extend radially outwardly and are inserted into the slot **129**. The engagement of the ends of the foil and spring elements in the slot **129** prevents the foil assembly from rotating when the  
15 shaft rotates. It is also possible to employ foil assemblies comprising a plurality (e.g., three) of arcuate spring element segments and foil segments that collectively form a full circumferential foil assembly, wherein the edges of the spring elements and foil segments fit into the slots **129** to prevent rotation. The foil or foil segments generally comprise a metal substrate having a friction-reducing coating on the radially inner  
20 surface that faces the shaft. Various coatings can be employed, including but not limited to polymer-based coatings, metal oxide-based coatings (e.g., NASA PS 304), etc.

The second or inboard journal bearing **140** has a construction generally similar to that of the outboard journal bearing described above. The bearing includes a  
25 generally annular bearing carrier **142** installed in an inboard portion of the center housing bore **92** adjacent the turbine wheel **74**. The bearing carrier **142** can be made of a poor thermally conducting material such as stainless steel, ceramic, or the like. The bearing carrier **142** at its outboard end (i.e., the end adjacent the outboard bearing carrier **122**) has a tubular portion **143** provided by virtue of an axially extending  
30 recess **144** machined into the outboard face of the bearing carrier. The inner diameter of the tubular portion **143** and the outer diameter of the surface **130** of the inboard end of the outboard bearing carrier **122** are such that the end of the carrier **122** is received into the tubular portion **143** with a close fit (and, if desired, a slight interference fit,

although an interference fit is not essential) so that the two parts are coaxially aligned. The end of the tubular portion **143** abuts a step in the outer surface of the outboard bearing carrier **122**; the recess **144** in the inboard bearing carrier is axially longer than the end portion of the carrier **122** received into the recess, such that a space is defined  
5 between the carriers for containing a thrust bearing assembly, described below. The outer surface of the inboard bearing carrier **142** is stepped such that there is a larger-diameter portion that includes the tubular portion **143** at the outboard end, and a smaller-diameter portion **145** at the inboard end adjacent the turbine. The larger-diameter portion abuts an outboard-facing surface **146** (FIG. 4) of the center housing  
10 to prevent the bearing carrier **142** from moving axially toward the turbine.

The outer diameter of the larger-diameter portion of the carrier **142** has a diameter less than that of the inboard portion of the center housing bore **92** in which the bearing carrier **142** is installed. To locate the bearing carrier **142** radially within the bore **92**, an undulating ring **147** is mounted about the bearing carrier within a  
15 recess **148** in the outer surface of the smaller-diameter portion of the carrier **142**. The ring **147** undulates in the circumferential direction; its undulations project radially out from the outer surface of the bearing carrier and abut the inner surface of the bore **92** in the center housing. The ring **147** advantageously can comprise a tolerance ring. The ring is formed of a metal. To minimize heat transfer from the center housing to  
20 the bearing carrier **142**, the ring **147** advantageously comprises a material having a relatively low thermal conductivity, such as stainless steel or the like. In addition to its heat transfer-reducing function, the ring **147** may also help attenuate vibration and/or noise from shaft unbalance.

The tubular portion **143** of the bearing carrier **142** has four circumferentially  
25 spaced, elongate slots **149** extending radially through the tubular portion into the space that exists between the two bearing carriers **122**, **142**, for passing cooling air into such space to cool the thrust bearing assembly disposed therein. Further description of the thrust bearing assembly and the cooling system for the thrust and journal bearings is provided below.

30 A foil assembly substantially similar to that described above in connection with the outboard journal bearing **120** is installed within the inboard bearing carrier **142**. Accordingly, the description of this foil assembly is not repeated here for the

sake of brevity, except to note that the spring elements and foil or foil segments engage one of three axial slots **150** (only two of the slots visible in FIG. 6) in the inner surface **151** of the bearing carrier **142**.

The thrust bearing assembly **160** of the turbocharger comprises a thrust disk **162** disposed between a first or outboard thrust bearing assembly **164** and a second or inboard thrust bearing assembly **168**. In FIG. 6, the two thrust bearing assemblies **164**, **168** are shown only diagrammatically. FIG. 9 shows the entire thrust bearing assembly **160** in detailed exploded view, and FIG. 7 shows the thrust bearing assembly installed in the turbocharger. As seen in FIG. 7, a radially inner portion of the thrust disk **162** is captured between the shaft sleeve **52c** and the larger-diameter portion **52a** of the stepped shaft part; thus, the thrust disk moves axially with the shaft in response to pressure loads in the turbocharger. Depending on the operating condition, the shaft and thrust disk may move either outboard or inboard.

The outboard thrust bearing assembly **164** comprises a generally annular or ring-shaped spring element **165** and a generally annular or ring-shaped foil **166**. The inboard thrust bearing assembly **168** comprises a generally annular or ring-shaped spring element **169** and a generally annular or ring-shaped foil **170**. The outboard spring element **165** is disposed against the end face of the outboard bearing carrier **122** and the outboard foil **166** is disposed between that spring element and the thrust disk **162**. Similarly, the inboard spring element **169** is disposed against the end face of the inboard bearing carrier **142** and the inboard foil **170** is disposed between that spring element and the thrust disk **162**.

Various configurations of spring elements and foils can be used for the thrust bearings **164**, **168**. In the illustrated embodiment, the spring element **165** comprises an outer ring **165a** and a plurality of arcuate or sector-shaped spring segments **165b** spaced apart about a circumference at a location radially inward of the outer ring **165a**. The spring segments **165b** are attached to the outer ring **165a** by radial connecting webs **165c**. The spring segments **165b** are arranged in pairs, with the two segments of each pair being connected by a circumferential connecting web **165d**. The spring element **165** also includes at least two diametrically opposite fingers **165e** that project axially from the outer ring **165a** and engage holes in bearing insert **122** to

prevent rotation of the spring element **165** and to angularly locate the spring element. The spring segments **165b** have an undulating shape in the circumferential direction.

The inboard spring element **169** has a configuration corresponding to that of the outboard spring element. Thus, the spring element **169** has an outer ring **169a**,  
5 spring segments **169b**, radial connecting webs **169c**, circumferential connecting webs **169d**, and fingers **169e**, which correspond with the like elements of the outboard spring element.

The outboard foil **166** comprises an outer ring **166a** and a plurality of arcuate or sector-shaped foil segments **166b** spaced apart about a circumference at a location  
10 radially inward of the outer ring **166a**. The outer ring **166a** is discontinuous, comprising a plurality (e.g., three, as shown) of arcuate sections spaced about its circumference. The foil segments **166b** are attached to the outer ring **166a** by radial connecting webs **166c**. The foil segments **166b** are all connected by circumferential connecting webs **166d**. The foil **166** also includes at least two diametrically opposite  
15 fingers **166e** that project axially from the outer ring **166a** and engage the holes in the bearing insert **122** to angularly locate and prevent rotation of the foil **166**. The foil segments **166b** are structured and arranged to align with the spring segments **165b** of the spring element, such that each foil segment is backed up by a spring segment. The outer ring **166a** of the foil also aligns with the outer ring **165a** of the spring element.

20 The inboard foil **170** comprises an outer ring **170a** and a plurality of arcuate or sector-shaped foil segments **170b** spaced apart about a circumference at a location radially inward of the outer ring **170a**. The outer ring **170a** is discontinuous, comprising a plurality (e.g., six, as shown) of arcuate sections spaced about its circumference. The foil segments **170b** are attached to the outer ring **170a** by radial  
25 connecting webs **170c**. The foil segments **170b** are all connected by circumferential connecting webs **170d**. The foil **170** also includes at least two diametrically opposite fingers **170e** that project axially from the outer ring **170a** and engage holes in the bearing insert **142** to angularly locate and prevent rotation of the foil **170**. The foil segments **170b** are structured and arranged to align with the spring segments **169b** of  
30 the spring element, such that each foil segment is backed up by a spring segment. The outer ring **170a** of the foil also aligns with the outer ring **169a** of the spring element. The outer ring **170a** also defines a plurality of spring tabs **170f** that project in the

circumferential direction and obliquely relative to the plane of the foil **170**. Each arcuate section of the outer ring **170a** defines two of the spring tabs **170f** at its opposite ends, and the two tabs are angled in opposite oblique directions away from each other. The spring tabs **170f** are structured and arranged to contact the outer ring  
5 **166a** of the outboard foil **166**; the spring tabs bias the two foils away from the opposite faces of the thrust disk **162** to help prevent contact therebetween when the turbocharger is not rotating or is rotating at a very slow speed.

During assembly of the thrust bearing assembly **160** in the turbocharger, the fingers **165e** and **166e** of the outboard spring element and foil, which project out of  
10 plane toward the outboard bearing carrier **122**, are inserted into corresponding slots or holes defined in the adjacent end face of the carrier. This engagement prevents rotation of the spring element and foil, as previously noted. Similarly, the fingers **169e** and **170e** of the inboard spring element and foil are inserted into slots or holes defined in the adjacent end face of the inboard bearing carrier **142**.

15 One aspect of the present invention relates to the installation of the bearing assembly **100** in the center housing **90**. In particular, for ease of assembly, the bearing assembly **100** advantageously comprises a unit or cartridge comprising the foil thrust bearing assembly **160** retained between the first and second foil journal bearings **120** and **140** by virtue of the connection between the bearing carriers **122** and  
20 **142**. The bearing cartridge **100** and the center housing bore **92** are configured such that the bearing cartridge is insertable as a unit into the bore from the end of the center housing adjacent the compressor **60**.

Cooling of the foils of the journal and thrust bearings is a particular aspect of the present invention. The cooling system is now described with reference primarily  
25 to FIGS. 1-3. As previously noted, the center housing **90** defines a cooling air supply passage **94** that extends into the center housing bore **92**. Cooling air extracted from the engine intake duct **32** is supplied through a line **36** that connects to the supply passage **94**. The passage **94** opens into an annular space **95** that surrounds the bearing assembly **100**; the annular space **95** is provided by virtue of an annular groove or  
30 channel formed in the inner surface of the bore **92** in the center housing. The annular space **95** is aligned with the slots **149** in the inboard bearing carrier **142**. Thus, cooling air is supplied through the slots **149** into the thrust bearing **160**. The cooling

air supplied through the slots **149** proceeds radially inwardly and flows through the air space between each foil **166, 170** and the thrust disk **162** and also flows through the spaces defined between the foils and their respective bearing carriers **122, 142**. After flowing radially inwardly past the thrust bearings, the cooling air flows on each side of the thrust disk **162** are turned 90° to flow through the respective journal bearings **120, 140**. In this regard, and with reference to FIG. 8, it will be noted that the foil assembly defines a plurality of axially extending cooling passages by virtue of the undulating shapes of the spring elements **135, 136**.

The cooling air that cools the outboard journal bearing **120** then is turned radially outward and flows through the recesses **127** in the face of the bearing carrier **120** into an annular space **175** that surrounds the outboard end of the bearing carrier **120**. The annular space **175** is provided by virtue of a circumferential groove or channel formed in the inner surface of the center housing bore **92** at that location.

Similarly, the cooling air that cools the inboard journal bearing **140** is turned radially outward and flows into an annular space **176** that surrounds the inboard end of the bearing carrier **142**. The annular space **176** is provided by virtue of a circumferential groove or channel formed in the inner surface of the center housing bore **92** at that location.

The annular space **175** at the outboard side of the center housing connects to a passage **177** that leads into the cooling air discharge passage **96**. Likewise, the annular space **176** at the inboard side connects to a passage **178** that leads into the discharge passage **96**. Accordingly, the cooling air that cools the thrust and journal bearings is discharged through the passage **96**. The passage **96** connects to a line **37** that feeds the air back into the inlet duct **28** such that the cooling air is returned to the compressor **60**.

A portion of the cooling air supplied into the annular space **95** also flows axially between the outer surface of the bearing carrier **122** and the inner surface of the center housing bore. This is possible because, as previously noted, the maximum outer diameter of the bearing carrier is slightly less than the inner diameter of the center housing bore, and hence a small radial space exists therebetween. Additionally, although the undulating ring **131** mounted about the bearing carrier

abuts the inner surface of the bore, there are axial spaces between the ring and the bearing carrier by virtue of the undulations of the ring. Thus, some cooling air flows between the ring **131** and the carrier **122** into the annular space **175**. This cooling air assists in reducing heat transfer from the center housing to the bearing carrier **122**. (It should be noted that the inboard bearing carrier **142** abuts the center housing **90** on surface **146**, which effectively seals off the incoming air and prevents it passing through the inboard undulating ring **147** to the annular space **176**.) Additionally, there is limited surface area contact between the rings **131**, **147** and the center housing and bearing carriers, which reduces heat transfer therebetween. It is also advantageous to make the rings out of a material having poor thermal conductivity such as stainless steel or the like. Furthermore, the bearing carriers **122**, **142** advantageously are also made of a material having poor thermal conductivity, such as stainless steel, ceramic, or the like. These various measures help keep the journal bearings cooler.

In some applications, such as diesel engines, which tend to operate at relatively low peak cycle temperatures, adequate cooling of the foil bearings of the turbocharger may be achievable solely with the air cooling system described above. However, in other applications, such as gasoline engines that tend to run hotter, additional cooling measures may be needed, particularly if the low-friction coatings on the foils have a relatively low maximum allowable temperature (as, for example, some of the polymer type coatings have). Toward this end, the center housing **90** of the turbocharger **50** illustrated in the drawings includes a water jacket **200** comprising at least one cooling water passage that extends circumferentially about the bearing assembly **100**. Ports **202** and **204** extend from the outer surface of the center housing into the water jacket **200** for supplying cooling water into and discharging the cooling water from the water jacket. The ports are connected by suitable pipes or hoses (not shown) to the engine's coolant system. With reference to FIG. 5, a third port **206** is shown, but this port is used only during the process of casting the center housing, for passing a mold core support through the mold to support the mold core member. After the center housing is cast, the port **206** is plugged with a blind fitting (not shown).

Another aspect of the invention relates to the sealing arrangements for sealing the bearings. With reference to FIG. 3, at the compressor end of the bearing assembly 100, a piston ring or seal ring 180 is retained in a groove in the outer surface of the shaft sleeve 52c and abuts the radially inner surface of the support ring 132, with a radial compressive loading therebetween, to seal the interface between the shaft and support ring. The seal ring 180 comprises a metal, such as cast iron, stainless steel, or the like, and is a substantially 360-degree circular ring except for a narrow split that allows the ring to be deformed to install it in the groove in the shaft sleeve. Additionally, a resilient O-ring 182 is retained in a groove in the outer surface of the support ring 132 and is radially compressed between the support ring and the inner surface of the center housing bore 92 so as to seal the interface therebetween. The O-ring 182 comprises a resiliently elastic rubber or rubber-like material (e.g., silicone, fluoroelastomer such as VITON® available from DuPont Dow Elastomers L.L.C, etc.

At the turbine end of the bearing assembly 100, there is a single seal comprising a piston or seal ring 184 retained in a groove in the outer surface of the shaft portion 52a. The seal ring 184 is generally of the same type as the seal ring 180, previously described. The seal ring 184 abuts the inner surface of the center housing bore 92, with a radial compressive loading therebetween, to seal the interface between the shaft and center housing.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.